Unusually strong excitation of the 1.59 MeV 0+ state in the 100Mo(d,6Li)96Zr reaction

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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(79)90737-8

UNUSUALLY STRONG EXCITATION OF THE 1.59 MeV 0^+ STATE IN THE ^{100}Mo(d, ^{6}Li)^{96}Zr REACTION

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Received 29 December 1978

In a study of the ^{94,96,98,100}Mo(d, ^{6}Li)^{90,92,94,96}Zr reactions at E_d = 45 MeV an unusually strong excitation of the 1.59 MeV 0^+ state in ^{96}Zr is observed. The variation in the 0^+ strength from one zirconium isotope to the other can be qualitatively accounted for by the changing proton configuration with neutron number.

An important feature of α-transfer and pickup processes is their correlation with two-nucleon transfer reactions [1]. In a semi-microscopic description the structure amplitude for α-transfer can be factored into a two-neutron and a two-proton part. Thus for α-pickup on a chain of isotopes one will expect the relative strength to correlate with that of two-neutron pickup to the same final states, the protons acting as "spectators". In a study of the ^{94,96,98,100}Mo(d, ^{6}Li) ^{90,92,94,96}Zr reactions we observe marked deviations from this expectation. The apparent discrepancy may be explained by the known variation of the proton configuration in zirconium with neutron number.

Energy analysed beams of 45 MeV deuterons from the KVI AVF-cyclotron were used to bombard isotopically enriched targets (>95%) of metallic ^{94,96,98,100}Mo rolled to a thickness of approximately 300 μg/cm^2. Typical beam currents on target ranged from 200–400 nA. Reaction products were detected with a position sensitive multi-detector system [2] in the focal plane of the KVI QMG/2 magnetic spectrograph [3]. Events were recorded in descriptor mode on magnetic tape, and subsequently sorted and analysed off-line. By imposing several constraints on the data ^{6}Li ions could be clearly separated from the more abundant α-particles. The solid angle of the spectrograph was limited to 6 msr to ensure sufficient angular resolution. The energy resolution of 80 keV is mainly due to the target thickness, which was chosen as a compromise between obtaining maximum yield and optimum resolution. Absolute cross sections were determined by normalizing the reaction data to elastic deuteron scattering off the same targets which in turn was normalized to optical model predictions. The uncertainty in the absolute cross sections is estimated to be less than 15%.

Angle integrated spectra from the (d, ^{6}Li) reaction on the four Mo isotopes studied in this investigation are shown in fig. 1. Angular distributions have been obtained for all strong transitions to states below E_x ≈ 5 MeV, but for the following discussion we will limit ourselves to the $0^+ \to 0^+$ g.s. and lowest excited 0^+ state transitions. A more complete account of this work will be published elsewhere. Angular distributions for the $0^+ \to 0^+$ transitions are shown in fig. 2 together with DWBA predictions computed with optical model parameters listed in table 1. The calculations were performed with the computer code DWUCK [4] using a cluster form factor for the transferred α-particle.

The most striking observation of the present experiment is the very strong transition to the first excited 0^+ state in ^{96}Zr. The transition is as strong as the g.s. transitions leading to ^{90}Zr, ^{92}Zr and ^{94}Zr, and about 2.2 times as strong as the g.s. transition to ^{96}Zr. From the relative strength it seems as if the g.s. and the first excited state have been "interchanged" in ^{96}Zr. The relative strengths, corrected for Q-value effects are

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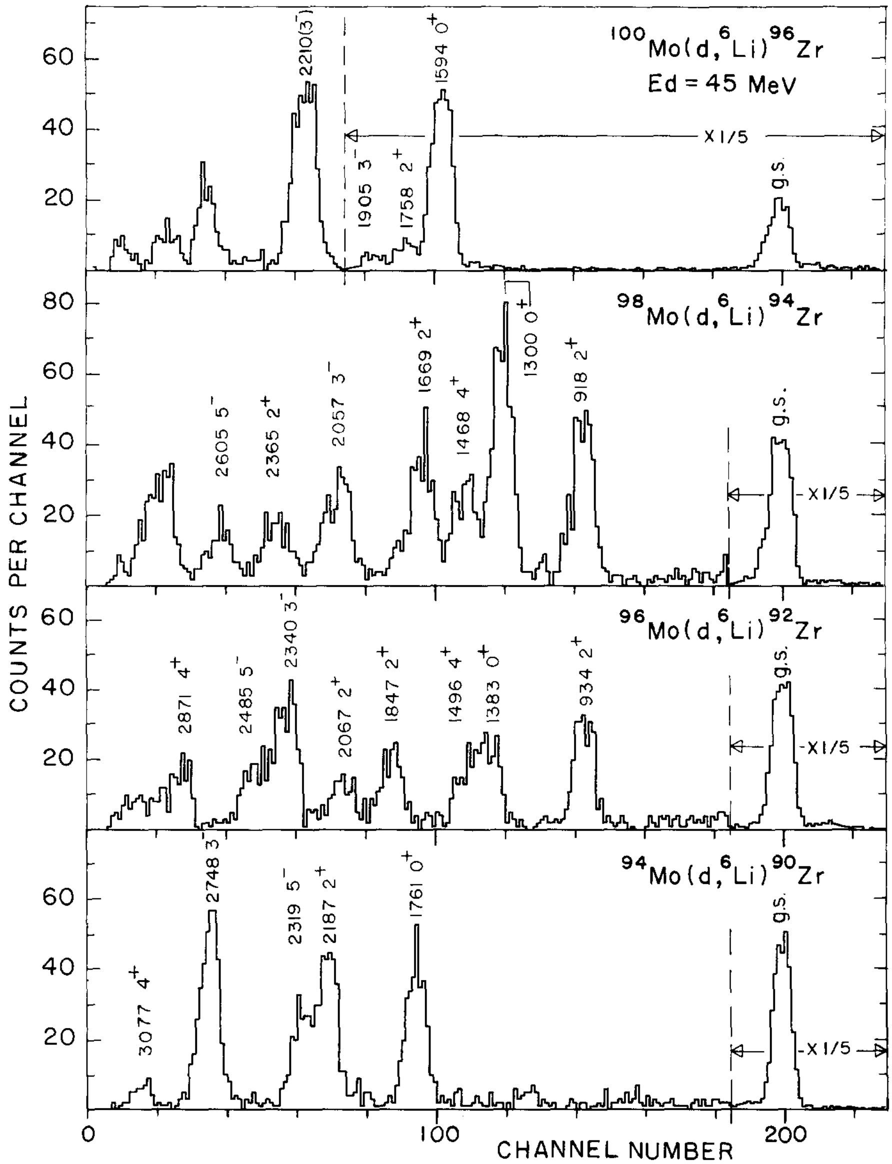

Fig. 1. Angle integrated (9°, 13°, 17°, 21°, 25°) spectra from the ^{94,96,98,100}Mo(d, ^{6}Li) reactions.

Table 1
Optical model parameters. Potentials in MeV, lengths in fm.

	V	r_0	a	W	$W' = 4W_D$	r_0'	a'	V_{so}	r_{so}	a_{so}	r_{0c}
d [a)]	76.96	1.25	0.7		42.0	1.25	0.86	6.0	1.25	0.7	1.3
^{6}Li [b)]	240.0	1.45	0.6	15.0		1.7	0.9				1.3
"α"		1.3	0.73								

a) Ref. [11].
b) Ref. [12], however, r_0 increased from 1.3 to 1.45 to fit $L = 0$ data.

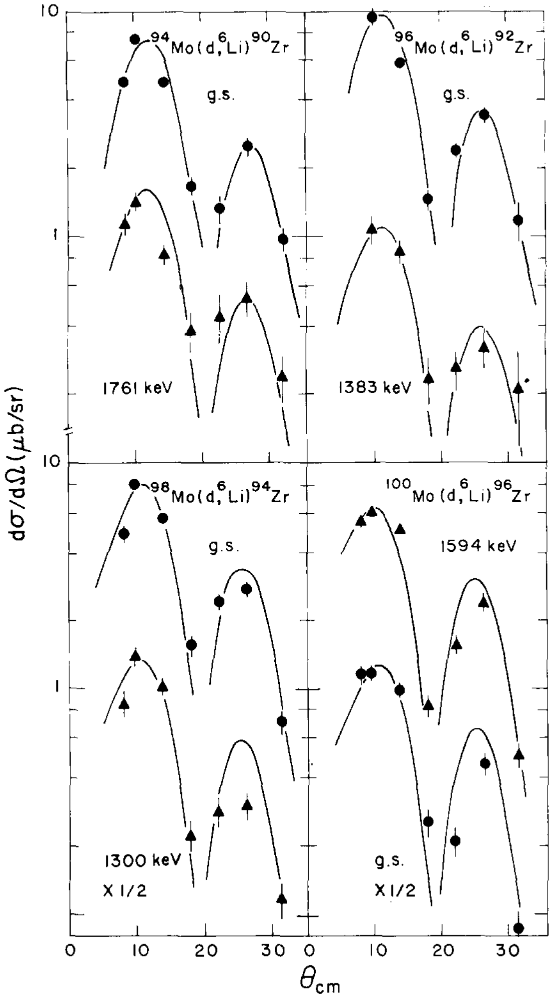

Fig. 2. Angular distributions of the transitions to the g.s. and lowest excited 0^+ states in $^{90,92,94,96}Zr$. The curves are the result of DWBA calculations with the parameters listed in table 1.

shown in fig. 3, together with the corresponding two-neutron pickup strengths from Zr(p, t) reaction studies [5]. Since ^{98}Zr is unstable, the $^{98}Zr(p, t)$ ^{96}Zr(g. s.) strength has been deduced from its inverse reaction [6]. There is no information available on the two-neutron pickup strength to the first excited 0^+ state in ^{96}Zr.

Very remarkably the α-pickup strengths do not correlate with the two-neutron strengths from the Zr(p, t) reaction. Two-neutron pickup to the g.s. of ^{96}Zr is very strong, whereas the (d, ^{6}Li) reaction to that state is weak. The (p, t) reaction only weakly

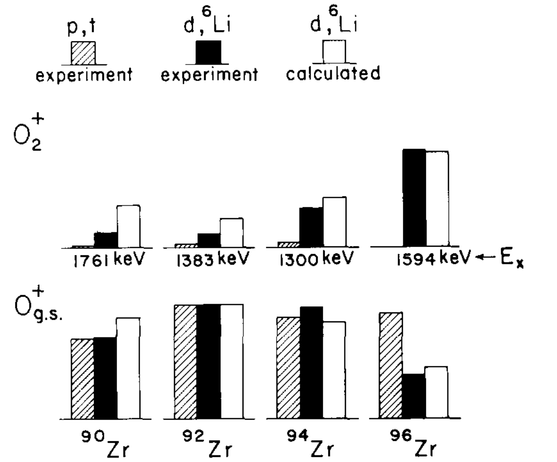

Fig. 3. Relative transition strengths from two-neutron pickup (shaded bars, experiment) and from the (d, ^{6}Li) reaction (black bars, experiment) to the g.s. and the lowest excited 0^+ states in ^{90}Zr, ^{92}Zr, ^{94}Zr and ^{96}Zr. The open bars are the results of corresponding calculations discussed in the text. All transitions have been normalized to the ^{92}Zr g.s. transition.

populates the lowest excited 0^+ states in ^{90}Zr, ^{92}Zr and ^{94}Zr, whereas these transitions are fairly strong in the (d, ^{6}Li) reaction. The latter observation is in agreement with the assumption [6] that the lowest excited 0^+ state in zirconium is mainly a proton excitation.

Flynn et al. [6] in two-neutron stripping on zirconium observed a strong transition to the first excited 0^+ state in ^{96}Zr that they relate to the $d_{5/2}$ subshell closure in ^{96}Zr. They suggest that the 0^+ state in ^{96}Zr be viewed as a type of neutron pairing vibrational state. This state should thus also be strongly excited in two-neutron pickup (which unfortunately cannot be measured) and in the (d, ^{6}Li) reaction in which that transition is indeed strong, though it is unexpected, that the transition to the pair vibrational state is much stronger than to the ground state. Neither can the possible neutron pairing vibrational character of the first excited 0^+ state, and the $d_{5/2}$ neutron subshell closure in ^{96}Zr, explain the discrepancy in the relative strengths of the (p, t) and the (d, ^{6}Li) data (fig. 3) leading to the g.s. of ^{96}Zr. The solution of this discrepancy will thus have to be sought in the proton configuration. Moreover, differences in the neutron configurations of zirconium and molybdenum between nuclei with the same neutron number as they manifest themselves e.g. in the (p, t) reaction [7], will have to be taken into account.

The proton configuration of the zirconium ground states is generally assumed to be of the form $\alpha_N(\pi p_{1/2})^2 + \beta_N(\pi g_{9/2})^2$. The first excited 0^+ state is the orthogonal state $\beta_N(\pi p_{1/2})^2 - \alpha_N(\pi g_{9/2})^2$. For the sake of simplicity we ignore the $p_{3/2}$ and $f_{5/2}$ proton excitations, and we assume the neutron configuration of the excited state to be the same as that of the g.s. The coefficients α_N and β_N can be obtained from proton pickup [8] and stripping [9] data. They are known to vary strongly with neutron number. The $(g_{9/2})^2$ admixtures to the g.s. are large for ^{90}Zr, ^{92}Zr and ^{94}Zr whereas the g.s. of ^{96}Zr is almost a pure $(p_{1/2})^2$ configuration [10]. We obtain $\alpha = 0.77, 0.71, 0.81$ and 0.95 for ^{90}Zr, ^{92}Zr, ^{94}Zr and ^{96}Zr, and $\beta = 0.64, 0.71, 0.59$ and 0.32 from the averages of the experimentally obtained values given in table 13 of ref. [9].

In order to obtain an estimate of the influence of the proton configuration we calculated the relative 0^+ cross sections with the simplifying assumption that the neutron transition strengths are the same from one nucleus to the other (neutrons acting as spectators). The relative cross sections for exciting the g.s. and the first excited 0^+ state, respectively, are thus given by the expressions:

$$(\mathrm{d}\sigma/\mathrm{d}\Omega)_{gs} \propto |R\alpha_N + \beta_N|^2 ,$$

and

$$(\mathrm{d}\sigma/\mathrm{d}\Omega)_{exc} \propto |R\beta_N - \alpha_N|^2 ,$$

where R^2 is the ratio of the cross sections for pickup of a $(g_{9/2})^2$ versus pickup of a $(p_{1/2})^2$ proton pair. We assume for this ratio 0.1, a value that seems quite reasonable taking into account that $p_{1/2}$ is a "hot orbital" [11]. We further assume that the proton configuration of the molybdenum isotopes is $(p_{1/2})^2_{0^+}$ $(g_{9/2})^2_{0^+}$ independent of neutron number. With these assumptions we obtain the following cross-section ratios for the $0^+ \to 0^+$ transitions: $(\sigma_{exc}/\sigma_{gs})_{^{96}Zr} = 1.85$, $(\sigma_{exc}/\sigma_{gs})_{^{94}Zr} = 0.54$ and $\{\sigma(^{94}Zr)/\sigma(^{96}Zr)\}_{gs} = 1.85$. The experimentally observed ratios are 2.24, 0.34 and 2.53. In view of the many assumptions made, this result is quite gratifying (see also fig. 3). Most importantly, this simple estimate correctly predicts those states that are strong and those that are weak.

More refined calculations, of course, will also have to take detailed neutron configurations of target and residual nucleus into account, in particular in view of the suggested pairing vibrational character [9] of the 0^+ excited state in ^{96}Zr, which may further enhance (or decrease) the transition to this state. There may also be effects associated with the onset of deformation around $A \approx 100$ in the molybdenum isotopes that are ignored in this paper.

From the present investigation it is concluded that in addition to the neutrons, the protons play a very active role in the (d, ^{6}Li) reaction on molybdenum isotopes, and that the change of their intrinsic configuration with neutron number can explain the observed variations in the $0^+ \to 0^+$ strengths. If this picture is correct the pattern seen in the (d, ^{6}Li) reactions should also be observed in two-proton pickup from the even-A molybdenum isotopes.

We thank A.G. Drentje and J.C. Vermeulen for their assistance in this experiment with the magnetic spectrograph and detector system, and the cyclotron crew for reliable operation of the machine. We also thank O. Hansen for a critical reading of the manuscript. This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (ZWO). One of us (G.D.J.) wishes to thank the UK SRC for financial support and the staff of the KVI for their help and hospitality during a very stimulating extended visit.

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